Determining the upper limit of Γ_{ee} for the $Y(4260)$

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By fitting the R values between 3.7 and 5.0 GeV measured by the BES collaboration, the upper limit of the electron width of the newly discovered resonance $Y(4260)$ is determined to be 240 eV at 90% C.L., together with the BABAR measurement on $\Gamma_{ee} \cdot \mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi)$, this implies a large decay width of $Y(4260) \to \pi^+\pi^- J/\psi$ final states.

1. Introduction

Recently, in studying the initial state radiation events, $e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$ (γ_{ISR}: initial state radiation photon) with 233 fb^{-1} data collected around $\sqrt{s} = 10.58$ GeV, BABAR collaboration observed an accumulation of events near 4.26 GeV/c^2 in the invariant-mass spectrum of $\pi^+\pi^- J/\psi$ [1]. The fit to the mass distribution yields 125 ± 23 events with a mass of $4259 \pm 8^{+2}_{-6}$ MeV/c^2 and a width of $88 \pm 23^{+6}_{-4}$ MeV/c^2. In addition, the following product is calculated

$$\Gamma(Y(4260) \to e^+e^-) \cdot \mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi)) \\ = 5.5 \pm 1.0^{+0.8}_{-0.7} \text{ eV}. \tag{1}$$

Since the resonance is produced in initial state radiation from e^+e^- collision, its quantum number $J^{PC} = 1^{--}$. However, this new resonance seems rather different from the known charmonium states with $J^{PC} = 1^{--}$ in the same mass scale, such as $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$. Being well above the $D\overline{D}$ threshold, instead of decaying predominantly into $D^{(*)}\bar{D}^{(*)}$ final states, the $Y(4260)$ shows strong coupling to $\pi^+\pi^- J/\psi$ final state. So this new resonance does not seem to be a usual charmonium state. The strange properties exhibited by the $Y(4260)$ have triggered many theoretical discussions [2]-[12].

One suggestion is that the $Y(4260)$ is the first orbital excitation of a diquark-antidiquark state ($[cs][\bar{c}\bar{s}]$) [2,3]. By virtue of this scheme, the mass of such a state is estimated to be 4.28 GeV/c^2, which is in good agreement with the observation. A crucial prediction of the scheme is that the $Y(4260)$ decays predominantly into $D_s\bar{D}_s$.

Another opinion favors hybrid explanation [4–7]. In the light of the lattice inspired flux-tube model, the calculation shows that the decays of hybrid meson are suppressed to pairs of ground state $1S$ conventional mesons [13,14]. This implies that decays of $Y(4260)$ into $D\bar{D}$, $D_s\bar{D}_s$, and $D_s^*\bar{D}_s^*$ are suppressed whereas $D^*\bar{D}$ and $D_s^*\bar{D}_s$ are small, and $D^{**}\bar{D}$, if above threshold, would dominate (P-wave charmonia are denoted by D^{**}). So it is interesting to search for the possible decay of $Y(4260) \to D_1(2420)\bar{D}$.

The third interpretation we like to mention is provide by Ref. [8], which suggests that the $Y(4260)$ is the second most massive state in charmonium family. The author ascribes the lack of $Y(4260)$ in $e^+e^- \to$ hadrons to the interference of S-D waves, and also estimates

$$\Gamma(Y(4260) \to e^+e^-) \simeq 0.2 - 0.35 \text{ keV} . \tag{2}$$

Besides the above interpretations, there are other kinds of proposals. The lattice study in Ref. [9] suggests that the $Y(4260)$ behaves like a $D_1\bar{D}$ molecule. In Ref. [10], it is proposed that

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the new state might be a baryonium, containing charms, configured by the Λ_c-$\overline{\Lambda}_c$. In Ref. [11], the $Y(4260)$ is considered as ρ-χ_{c1} molecule while in Ref. [12], the $Y(4260)$ is considered as ω-χ_{c1} molecule. However, all aforementioned speculations need further experimental judgment.

Most recently, CLEOc collected 13.2 pb^{-1} data at $\sqrt{s}$ = 4.26 GeV and investigated 16 decay modes with charmonium or light hadrons [15], and the channels with more than 3σ statistical significance are $\pi^+\pi^- J/\psi$ (11σ), $\pi^0\pi^0 J/\psi$ (5.1σ), and $K^+K^- J/\psi$ (3.7σ). No compelling evidence is found for any other decay modes for the $Y(4260)$, neither for the $\psi(4040)$ and $\psi(4160)$ resonances [15]. These measurements disfavor the ρ-χ_{c1} molecular model [11], baryonium model [10], and high charmonium state explanation [8]. So far as other survived speculations are concerned, such as charmonium hybrid [4–7], tetraqark model [2,3], $D_1\bar{D}$ molecule suggestion, and ω-χ_{c1} molecule explanation [12], further experimental studies are needed to make more definitive conclusions.

Since the $Y(4260)$ was observed in e^+e^- annihilation, it is expected that it contributes to the total hadronic cross section in e^+e^- annihilation (or R values in other words). The most recent such data on R measurements are from the BES experiment [18,19], as shown in Fig. 1 for $E_{c.m.}(=\sqrt{s})$ from 3.7 to 5.0 GeV. If we look in detail within the range from 4.25 to 4.30 GeV (refer to the inset of Fig. 1), it seems there is a bump around 4.27 GeV. Has this structure connection with the $Y(4260)$? We try to answer this question in this Letter. As there are other resonances nearby, we shall fit the full spectrum between 3.7 to 5.0 GeV in order to get the information on the $Y(4260)$.

2. Fit the ψ-resonances

The R values [18,19] used in this analysis were measured with the Beijing Spectrometer (BESII), which is a conventional solenoidal detector expounded in Ref. [16]. In the analysis below, the R values are converted into cross section $\sigma(e^+e^-)$ by multiplying the Born order cross section of $e^+e^- \to \mu^+\mu^-$. These cross sections are plotted in Fig. 2. There are clear peaks of $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$. The data points have been used to obtained the parameters of the ψ-resonances [17].

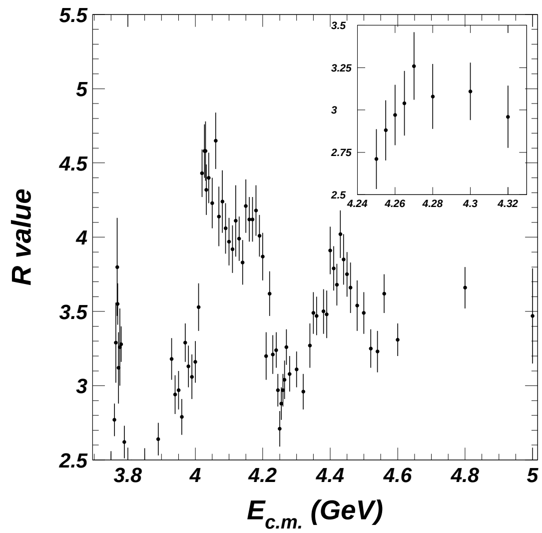


Figure 1. R values for $E_{c.m.}$ from 3.7 to 5.0 GeV measured by the BES collaboration [18,19]. The inset shows the R values in the vicinity of the $Y(4260)$.

To acquire the resonance parameters, we could simply fit the data set with cross section formula, each resonance with a Breit-Wigner

$$\sigma_j(s) = \frac{12\pi\Gamma_h^j\Gamma_{ee}^j}{[s-(M^j)^2]^2+(M^j\Gamma_t^j)^2} \ , \tag{3}$$

where Γ_{ee}, Γ_h, and Γ_t are the mass independent electronic, hadronic and total widths, respectively, for a vector resonance of mass M produced in the head-on collision of e^+ and e^-. Notice that $\Gamma_{ee} \ll \Gamma_t$ in our analysis, the approximation $\Gamma_h \approx \Gamma_t$ is actually adopted hereinafter. The summation of all the cross sections within the range we are studying is

$$\sigma_1(s) = \sum_{j=1}^{4}\sigma_j(s) \ , \tag{4}$$

where indices 1, 2, 3, and 4 denote four resonances $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$, respectively.

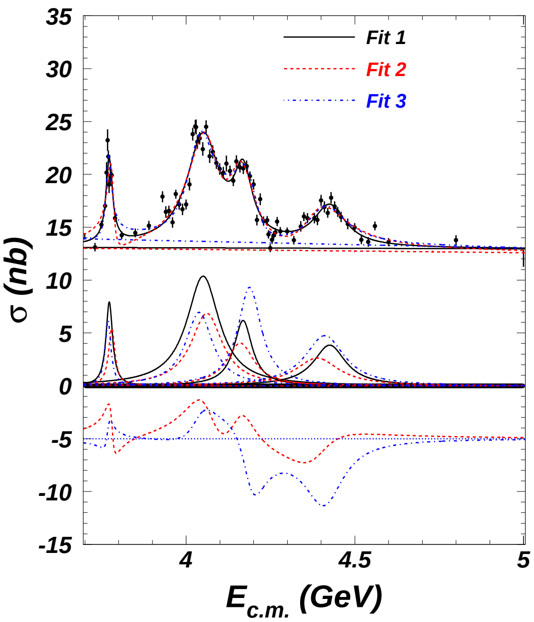


Figure 2. Total hadronic cross section in nb obtained as $\sigma(e^+e^- \to \text{hadrons}) = R \cdot 86.85/s$ (s in GeV^2) from R values in Refs. [18,19]. Three sets of fit results, Fit 1, Fit 2, and Fit 3 correspond to three cross section forms σ_1, σ_2, and σ_3 as described in text. Two interference curves have been moved downward by 5 nb for display purpose, the dashed line at -5 nb corresponds to zero cross section in the fit.

In the ψ-family resonance region, if we assume that all two-body $D^{(*)}\bar{D}^{(*)}$ states are decay products of resonance, and not produced directly in continuum, we could therefore treat resonance and continuum incoherently. Nevertheless, for the four wide resonances, they are close and are expected to have some same decay final states, there must be interference between any two of the resonances. Therefore the amplitudes corresponding to each resonance, with the following form

$$T_j(s) = \frac{\frac{1}{2}\sqrt{12\pi\Gamma_h^j\Gamma_{ee}^j}}{[s-(M^j)^2] + iM^j\Gamma_t^j} \ , \tag{5}$$

have to be added coherently to give the total amplitude that, once squared, will contain interferences of the type $\Re T_i^* T_j$. If the resonances are quite broad, the interference effect can also distort the resonance shape, the width might appear broader or narrower, and the position of the peak can be displaced as well. In this case, the total cross section

$$\sigma_2(s) = \left|\sum_{j=1}^{4} T_j(s)\right|^2 , \tag{6}$$

where $T_j(s)$ is given in Eq. (5).

So far as amplitude is concerned, in principle, there are presumably relative phases between different amplitudes besides the phase due to complex Breit-Wigner formula itself. So a more comprehensive total cross section would be the summation of amplitudes together with an additional phase, viz.

$$\sigma_3(s) = \left|\sum_{j=1}^{4} T_j(s)e^{-i\phi_j}\right|^2 . \tag{7}$$

Since what we actually obtain is the module square of amplitudes, only three relative phases could be detected in practice.

The standard chi-square estimator is constructed as follows

$$\chi^2 = \sum_{j=1}^{n} \frac{(\sigma^{exp}(s_j) - \sigma^{the}(s_j))^2}{(\Delta\sigma^{exp}(s_j))^2}, \tag{8}$$

where $\sigma^{exp}(s_j)$ indicates the experimentally measured cross section at the j-th energy point, while $\sigma^{the}(s_j)$ is the corresponding theoretical expectation at this energy point, which is composed of two parts

$$\sigma^{the}(s_j) = \sigma^{res}(s_j) + \sigma^{con}(s_j) \ , \tag{9}$$

where σ^{con} denotes the contribution from continuum. Since there is little evidence in the data for any substantial variation of the continuum background within the studied energy region, we parameterize the continuum cross section with a linear function

$$\sigma_{bg}(s) = A + B(\sqrt{s} - 3.700), (s \text{ in GeV}^2), \tag{10}$$

as has been used in Ref. [17]. Here we consider the continuum contribution as the background

for measurement of resonance parameters, that is $\sigma_{bg}(s) = \sigma^{con}(s)$.

In Eq. (9) σ^{res} denotes the contribution from resonances. The fit results are displayed in Fig. 2 where Fit 1, Fit 2, and Fit 3 correspond to the three cross section forms σ_1, σ_2, and σ_3, as expressed in Eqs. (4), (6), and (7), respectively. Although the synthetic curves for three fits are almost the same, as we expected, the interference effect deforms each resonance significantly, according to Fig. 2, $\psi(3770)$ and $\psi(4040)$ become narrower while $\psi(4160)$ and $\psi(4415)$ become wider when inference effect included. There exist constructive interferences as well as destructive ones, and the interference behaviors for amplitudes with and without extra phases are also very distinct. The fit results indicate that Γ_{ee} is very sensitive to the fit strategy, and the largest difference between various amalgamation strategies could reach 50%.

Since $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ have similar decay feature, that is, all decay dominantly to $D^{(*)}\bar{D}^{(*)}$ final states, we prefer the synthetic scheme of amplitude with phase which takes into account all possible interactions between resonances. So far as the $Y(4260)$ is concerned, the study of BABAR collaboration [1] implies that this new state may not be a common charmonium state, whose decay feature is rather distinctive from other ψ-family members, and this also obtains support from recent CLEOc measurements [15]. Therefore we add the $Y(4260)$ contribution incoherently to the total cross sections in Eqs. (4), (6), or (7). In this scheme, the upper limit of the production of the $Y(4260)$ in e^+e^- annihilation is determined, as expounded in the following section.

3. Determination of Γ_{ee} of the $Y(4260)$

Various fits to the data tell us that with limited knowledge on the nature of the resonances and comparatively meager data, we could only determine the Γ_{ee} of the $Y(4260)$ by a scan method. Specifically, we fix the mass of the $Y(4260)$ at 4.259 GeV/c^2 measured by BABAR collaboration [1], and scan over the $\Gamma_t \in (20, 180)$ MeV/c^2 (8 MeV/c^2 step) and $\Gamma_{ee} \in (0, 500)$ eV/c^2 (10 eV/c^2 step) parameter space. In order to avoid some grotesque fit results due to random effect of the $Y(4260)$ on the resonances nearby, in the scan procedure, the lower and upper bounds of the masses (total widths) are fixed to be 4100 and 4220 MeV/c^2 (30 and 250 MeV/c^2) and 4350 and 4500 MeV/c^2 (30 and 300 MeV/c^2) for $\psi(4160)$ and $\psi(4415)$, respectively.

Fig. 3 shows the likelihood as a function of the Γ_t and Γ_{ee} of the $Y(4260)$, with the likelihood function defined as

$$\begin{aligned}\mathcal{L}_w(\Gamma^i_{ee}, \Gamma^j_t) &= f_N \cdot \mathcal{L}_r(\Gamma^i_{ee}, \Gamma^j_t) \times \\ & \frac{1}{\sqrt{2\pi}\sigma_{\Gamma_t}} \exp\left(-\frac{(\Gamma^j_t - \Gamma_t)^2}{\sigma^2_{\Gamma_t}}\right) \ ,\end{aligned} \tag{11}$$

where

$$\mathcal{L}_r(\Gamma^i_{ee}, \Gamma^j_t) = \exp\left(-\frac{1}{2}\chi^2(\Gamma^i_{ee}, \Gamma^j_t)\right) \ . \tag{12}$$

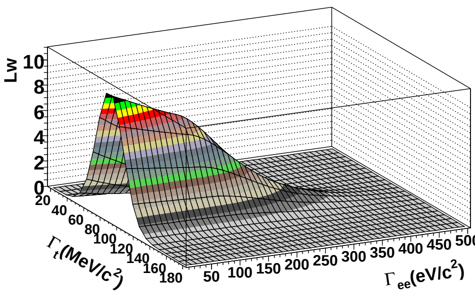
Here the χ^2 is determined from Eq. (8), and f_N an arbitrary normalization factor. The Gaussian term in Eq. (11) indicates that the measured width of the $Y(4260)$ [1] is considered assuming Γ^i_t distributed as a Gaussian with the mean value $\Gamma_t = 88$ MeV/c^2 and the standard deviation $\sigma_{\Gamma_t} = 23.8$ MeV/c^2. Summing $\mathcal{L}_w(\Gamma^i_{ee}, \Gamma^j_t)$ with respect to Γ^j_t, we obtain the variation of $\mathcal{L}_w$ versus Γ_{ee} as shown in Fig. 3(b). The integral of the likelihood curve gives the upper limit of Γ_{ee} of the $Y(4260)$ at 90% confidence level (C.L.):

$$\Gamma^{Y(4260)}_{ee} < 240 \text{ eV}/c^2 \ . \tag{13}$$

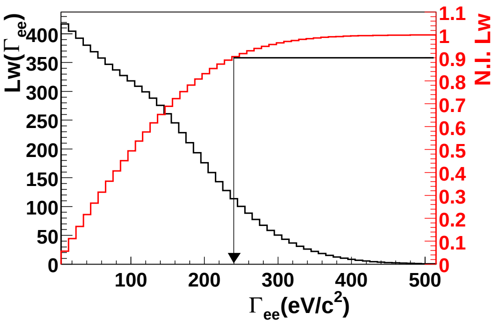
By virtue of Fig. 3(a), we sum up $\mathcal{L}_w(\Gamma^i_{ee}, \Gamma^j_t)$ with respect to Γ^i_{ee} to 90% fraction of the total area then obtain the upper limit of $\Gamma^{Y(4260)}_{ee}$ at 90% C.L. for each $\Gamma^{Y(4260)}_t$. So we obtain the variation of the upper limit of Γ_{ee} versus Γ_t as shown in Fig. 4. All the points are almost in a straight line, which indicates the ratio of the two quantities, or the upper limit of the branching fraction of $Y(4260) \to e^+e^-$ does not depend on the total width. Take the slope of the straight line in Fig. 4, we get

$$\mathcal{B}(Y(4260) \to e^+e^-) < 2.4 \times 10^{-6},$$

at 90% C.L.



(a) $\mathcal{L}_w$ w.r.t Γ_{ee} v.s. Γ_t



(b) $\mathcal{L}_w$ w.r.t. Γ_{ee}

Figure 3. Relative likelihood ($\mathcal{L}_w$) distribution with respect to (w.r.t.) Γ_{ee} and Γ_t (a); and to Γ_{ee} with Γ_t integrated (b). The "N.I." in (b) indicates normalized integral value for $\mathcal{L}_w$.

4. Other possibilities

Although it is reasonable to treat the $Y(4260)$ as an independent resonance in the fit and all the ψ-resonances are synthesized by amplitudes with phases, one may argue that other possibilities could exist since there is limited information about the properties of the $Y(4260)$ as well as the other ψ-resonances. Thereby it's better to take a variety of effects into consideration.

First, there are totally three categories or six schemes for summation of all the resonances in this analysis:

1. The cross section of the $Y(4260)$ is added directly with the other four resonances which are summed through cross sections, amplitudes, or amplitudes together with relative phases, as we discussed in Sect. 2.

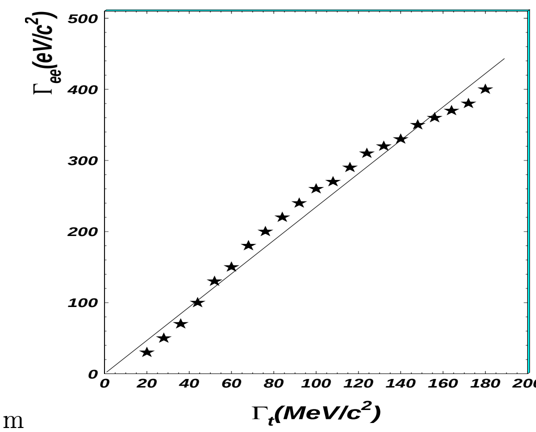


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Figure 4. The variation of the upper limit of Γ_{ee} at 90% C.L. with respect to Γ_t. The slope of the solid line denotes the averaged ratio $\Gamma_{ee}/\Gamma_t = 2.4 \times 10^{-6}$.

2. The amplitude of the $Y(4260)$ is synthesized with other four resonances which are combined through amplitudes, or amplitudes together with relative phases.

3. The five amplitudes corresponding to resonances $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, and $\psi(4260)$, with relative phases are summed up to give the final synthetic cross section.

Second, we consider the effect of different background shapes in the fit. In Sect. 2, we adopt the first order polynomial to depict the background, nevertheless, higher order polynomial can be used to delineate the background as well.

In addition, we notice one background shape once adopted by DASP group, who tried to take into account the threshold effect of the charmed mesons [20],

$$\sigma_{dasp} = \sigma_{e^+e^- \to \mu^+\mu^-} \cdot (A_0 + \sum_{j=1}^{6} A_j \beta_j^3 F^2), \quad (14)$$

with

$$F = \frac{1}{1 - s/(3.1 \text{ GeV })^2} \ , \quad (15)$$

where A_0 describes the contribution from continuum; j ranging from 1 to 6 indicates the $D\overline{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$, $D_s\bar{D}_s$, $D_s\bar{D}_s^*$, $D_s^*\bar{D}_s^*$ thresholds, respectively. A_j are free parameters; β_j is the velocity of the relevant particles; and F is a oversimplified form factor defined above.

The fit results show that the effect of polynomial background is at the same level with or smaller than the DASP background, so as an estimation, we adopt the linear and the DASP backgrounds as two typical cases for background description.

Last, we also consider the possible energy-dependent Γ_t of the $Y(4260)$. There are arguments in some references [3–6] that the $Y(4260)$ may be due to threshold effect just as the $\psi(3770)$, so the Γ_t of the $Y(4260)$ could be energy dependent as follows:

$$\begin{aligned}\Gamma_t(W) &= \overline{\Gamma}_t \cdot \theta(W-2m_{D_s^{*\pm}})\times \\ &\frac{p^3_{D_s^{*\pm}}}{1+(rp_{D_s^{*\pm}})^2}\cdot\frac{1+(r\overline{p}_{D_s^{*\pm}})^2}{\overline{p}^3_{D_s^{*\pm}}} \;. \end{aligned} \tag{16}$$

Here $\overline{\Gamma}_t = \Gamma_t(M)$, $W=\sqrt{s}$ is center-of-mass energy, r the classical interaction radium, and p the $D_s^{*\pm}$ momentum, reads explicitly as

$$p_{D_s^{*\pm}} = \frac{1}{2}\sqrt{W^2-4m^2_{D_s^{*\pm}}} \; ; \tag{17}$$

and $\overline{p}$ is the $D_s^{*\pm}$ momentum at resonance peak, viz.

$$\overline{p}_{D_s^{*\pm}} \equiv p_{D_s^{*\pm}}\Big|_{W=M} = \frac{1}{2}\sqrt{M^2-4m^2_{D_s^{*\pm}}} \; . \tag{18}$$

So Γ_t in amplitude expression (5) should be replace by the form expressed in Eq. (16) for the $Y(4260)$.

In a word, considering different summation schemes, background shapes, energy-dependent forms of the total width, a series of results give the upper limit of Γ_{ee} ranges from 20 to 470 eV$/c^2$ at 90% C.L.

5. Discussion

Our study indicates that the upper limit of Γ_{ee} of the $Y(4260)$ is about 240 eV$/c^2$, which is consistent with the estimation presented in Eq. (2).

Utilizing our upper limit $\Gamma_{ee}=240$ eV$/c^2$ for the $Y(4260)$, together with the relation of Eq. (1), we obtain the lower limit of branching fraction at 90% C.L. to be

$$\mathcal{B}(Y(4260)\to\pi^+\pi^-J/\psi) > 1.8\% \; .$$

This means that the partial width $\Gamma(Y(4260)\to\pi^+\pi^-J/\psi) \geq 1.6$ MeV$/c^2$ at 90% C.L., which is much larger than the corresponding partial widths of ψ' (89.1 keV$/c^2$) [21] and ψ'' (44.6 keV$/c^2$) [21,22], respectively.

CLEOc measured the cross section for $\pi^+\pi^-J/\psi$ channel to be 58 pb^{-1} [15], which is consist with BABAR result, 50 pb^{-1} [1]. As a conservative estimation, we regard the central value calculated in Eq. (1) is the same for CLEOc and BABAR, but adopt the improved accuracy prvoided by CELO, then we can obtain the following lower limits at 90% C.L.

$$\begin{aligned}\mathcal{B}(Y(4260)\to\pi^+\pi^-J/\psi) &> 1.9\% \;, \\ \mathcal{B}(Y(4260)\to\pi^0\pi^0J/\psi) &> 0.7\% \;, \\ \mathcal{B}(Y(4260)\to K^+K^-J/\psi) &> 0.2\% \;,\end{aligned}$$

and

$$\mathcal{B}(Y(4260)\to XJ/\psi) > 3.4\% \;,$$

where X denotes (the numbers of the observed events by CLEOc are presented in parathses) $\pi^+\pi^-(37)$, $\pi^0\pi^0(8)$, $K^+K^-(3)$, $\eta(5)$, $\pi^0(1)$, $\eta'(0)$, $\pi^+\pi^-\pi^0(0)$, and $\eta\eta(1)$.

As we notice up till now only results on hidden-charm final states were reported about the $Y(4260)$, measurements involving open-charm are anxiously awaited to confirm existing speculations or provide clues for further theoretical inquiry. In addition, more accurate Γ_{ee} is still needed for a better understanding the nature of the $Y(4260)$.

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